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Experimental Validation of the Ultimate Limit State Limit Equilibrium Analysis (ULSLEA) with Results from Frame Tests

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ABSTRACT

The simplified structural analysis procedure to determine the ultimate limit state lateral load capacities of steel, template-type offshore platforms is identified as ULSLEA (Ultimate Limit State Limit Equilibrium Analysis) (Mortazavi, Bea, 1994). Simplified formulations have been developed to estimate the ultimate lateral shear capacity of the three primary structural components of a platform; deck legs, jacket, and foundation. The validation of ULSLEA using experimental results from laboratory tests on two-dimensional frames is described in this paper. Lateral loading capacity results developed by ULSLEA are compared with results from three sets of experimental frame tests (Grenda, et al. 1989; Bolt, et al, 1994; 1995). ULSLEA was able to predict the ultimate capacity of the six test frames very well. Defining a bias as the ratio of test over ULSLEA results, the mean and coefficient of variation of the bias were estimated to be 1.05 and 0.1, respectively, for the cases where brace failures governed the capacity. In cases where tubular joint failures governed the frame capacity, the mean and coefficient of variation of the bias were estimated to be 2.03 and 0.01 respectively. The latter set of results can be explained by the conservatism of the API joint capacity equations (API, 1993b), which were used in the ULSLEA analyses. If the bias in the conservative API joint capacity equations are recognized (approximately 2), the ULSLEA capacity bias is approximately 1.0.

Key Words: platforms, capacities, ultimate limit state performance, failure, simplified methods

INTRODUCTION

The simplified nonlinear structural analysis procedure for template-type offshore platforms, developed previously by the authors, is identified as ULSLEA (Ultimate Limit State Limit Equilibrium Analysis) (Mortazavi, Bea, 1994). In this procedure, the structure is defined by specifying the following parameters: the effective deck areas, the proportion and topology of jacket legs, braces, joints, foundation piles (main piles through the legs and skirt piles), well conductors, and effective areas of appurtenances (e.g. boat landings, pipeline risers). Specialized elements are designated including grouted or ungrouted joints, braces, and legs. In addition, damaged or defective elements are included. Dent depth and initial out-of-straightness are specified for braces with dents and global bending defects. Element capacity reduction factors are introduced to account for other types of damage to joints, braces, and foundation (corrosion, fatigue cracks, etc.). Similar algorithms are included to characterize repaired elements (e.g. grout filled braces). Steel elastic modulus, yield strength, and effective buckling length factor for vertical diagonal braces are specified.

Simplified formulations are developed to estimate the ultimate lateral shear capacity of the three primary structural components of a platform; deck legs, jacket, and foundation. Elements within these components are identified first. These are deck legs, tubular braces and their connections (tubular joints) and main and skirt piles. For each component to fail, all elements within that component have to fail. Based on past numerical analyses and experience, failure modes are assumed for different platform components. Using the concept of plastic hinge theory, the principle of virtual work is utilized to formulate the component capacities; the virtual displacement is

taken to be the actual collapse mechanism and an equilibrium equation is derived for each component at ultimate limit state. Where of significance, geometric nonlinearities are taken into account.

During the first generation verifications, ULSLEA was verified with resutls from detailed three-dimensional nonlinear pushover analyses performed on six Gulf of Mexico platforms (Bea, DesRoches, 1993; Bea, 1995). Defining the bias as the ratio of the nonlinear pushover analysis Reserve Strength Ratio (RSR = ratio of maximum lateral loading capacity to reference lateral loading) to the RSR determined using ULSLEA, the first generation verifications developed RSR biases in the range of B_{RSR} = 0.80 to 1.03 with a mean value of 0.95. Several of the verification platforms were subjected to intense loadings developed by hurricanes. The predicted and observed performance characteristics of the platforms were in good agreement.

During the second generation verifications (Bea, Mortazavi, 1995; Bea, Loch, Young, 1995; Bea, et al., 1995) ULSLEA was verified with results from detailed three-dimensional nonlinear pushover analyses performed on six Gulf of Mexico platforms. The detailed analyses were performed using the programs WAJAC (DNV, 1993) and USFOS (SINTEF, 1994).

Defining the bias as the ratio of USFOS to ULSLEA ultimate lateral loading capacities, the mean and the coefficient of variation of the bias are 1.03 and 0.09, respectively. These results indicate that compared with detailed nonlinear analyses, the simplified method predicts ultimate capacities that are practically unbiased. In addition, comparison of the results from the ULSLEA analyses with the performance characteristics of these platforms in past intense hurricanes indicates that the analyses produce results that are in agreement with the observed characteristics.

These biases and uncertainties are remarkably small. Experience during the past two years in analyzing more than 20 platforms indicates that the simplified ULSLEA analyses have taken from 1/30th to 1/60th of the time required to perform the complex USFOS analyses. In the majority of these analyses, ULSLEA results were able to identify errors in the initial USFOS results. The anticipated benefits of the simplified methods have been realized.

In the remainder of this paper we will describe the validation of ULSLEA that has been accomplished by comparing the capacities predicted by ULSLEA with those determined from experimental tests performed on two-dimensional test frames typical of those found in template-type platforms.

FRAME TEST PROGRAM I

Frame test program I was performed in 1986 in behalf of Esso Australia. The frame tests were performed to provide experimental background for upgrading some of Esso Australia's older platforms in the Bass Strait (Grenda et al., 1988). The program was conducted to support the results of nonlinear pushover analyses and the modeling assumptions upon which the analyses were based. Verification of these modeling assumptions were crucial to the validity of the nonlinear analyses results.

The test program included static testing of six two-dimensional single-bay K-braced frames (Figure 1). Four of the frames were ungrouted with overlap-joints. In two other cases, the compression diagonals were grout-filled. The tubulars were fabricated from steel plate similar to steel conforming to the ASTM A36 specification (API Grade B/X42). The measured static yield strengths were 1.2 to 1.3 times the nominal yield strength. Two different K-joint can thicknesses were selected. The frames were heavily instrumented and sophisticated data acquisition systems were utilized. The 25 ft. by 28 ft. frames were loaded laterally using a 250 ton displacement-controlled hydraulic cylinder.

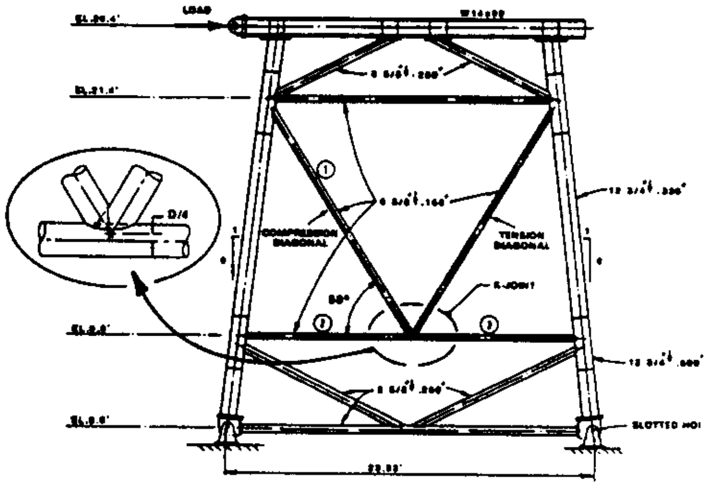

Figure 1: Test Program I - Test Frame Geometry (After Grenda et al.,1988)

Figure 2 shows the load-displacement response of test frames 1-6. The performance of the four ungrouted frames with different joint can thicknesses (tests 1-4) was reported to be similar, each resisting a peak lateral load of approximately 160 kips. In all four cases, the buckling of compression braces was reported to govern the behavior of the frames. The lateral load resisting capacity of the frames began to decrease rapidly after failure of the compression diagonals. This is a typical result for this brittle k-braced frame configuration. The measured effective length factors for the K-brace compression diagonals at peak load in the four ungrouted frame tests varied between 0.53 and 0.63 based on the node-to-node length of the members. The tests indicated an insensitivity of the measured frame behavior to the thickness of the K-joint cans. The apparent insensitivity to K-joint can thickness was attributed to the relatively high degree of brace overlap at the K-node (Figure 1).

In all four cases, ULSLEA was able to predict the frame failure at the same peak lateral loads (Figure 2).

The lateral load capacity of the frames was significantly increased by grouting the diagonal compression braces. Grouting increased the buckling capacity of the diagonal braces in compression so that the diagonal braces in tension were able to fully develop their tensile capacity. This effect resulted in a redundant behavior of the frames. At the time the peak load was reached, both diagonal braces in tension and compression were contributing to the lateral shear resistance with their ultimate strengths. In addition, due to large displacement at collapse, the full portal strength of the frame legs were reported to be developed. However, the observed increase in lateral frame capacity due to frame action should not be overemphasized. In a real multi-bay offshore structure, frame action within one bay is likely to result in failure of diagonals in neighboring bays.

Frame test 6 resulted in an ultimate frame capacity of roughly 300 kips. The result gained using the simplified ULSLEA method indicated an almost simultaneous failure of two diagonal braces at a collapse load of roughly 240 kips (Figure 3). This is an underestimation of 20% compared to the test results. A detailed comparison of predicted and actual member forces at collapse indicated that the effect of frame action, observed in the test, was the source of the difference in results. ULSLEA does not take the effect of frame action into account.

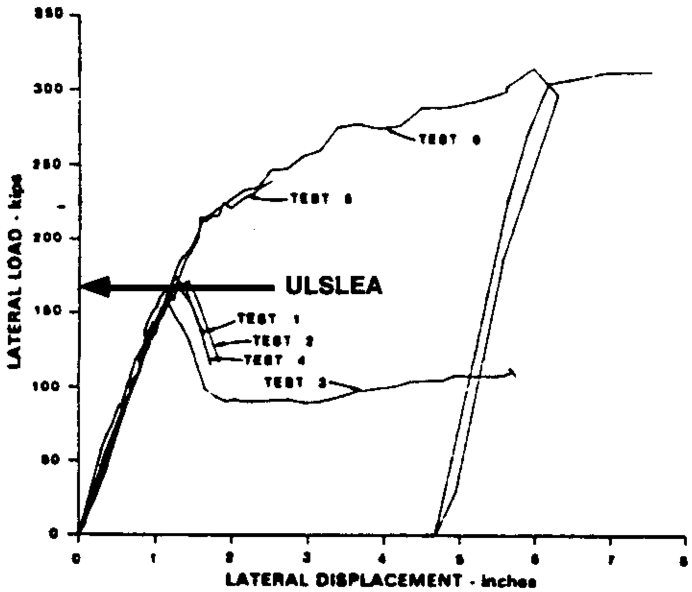

Figure 2: Test Program I - Tests 1-4 Ungrouted Compression Diagonals (After Grenda et al., 1988)

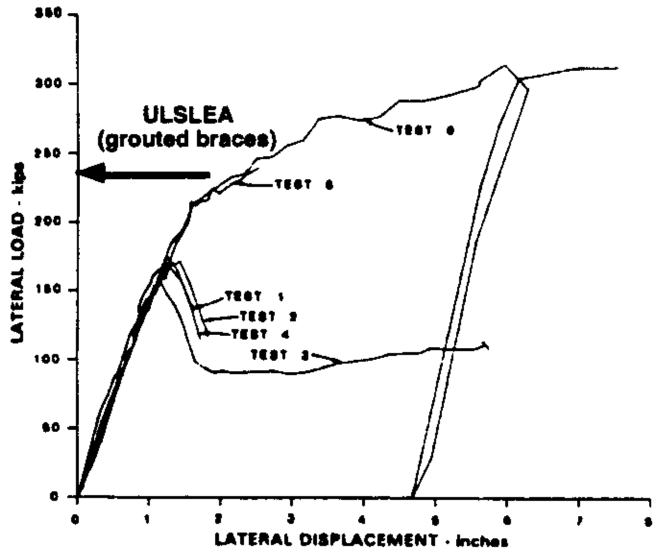

Figure 3: Test Program I - Tests 5-6 (After Grenda et al.,1988)

FRAME TEST PROGRAM II

Frame test program II was initiated in the U.K. in 1987. The program, Frames Project Phase I, was conducted by Billington Osborne-Moss Engineering Limited (BOMEL) as part of a joint industry project with the objectives of providing test data on the collapse behavior of jacket structures and developing a calibrated software for the nonlinear pushover analysis of framed structures (Bolt et al., 1994). Prior to release of the test data, the Health and Safety Executive in the U.K. invited interested companies in the U.K., Norway and U.S. to participate in a benchmarking effort. The results of this benchmarking exercise have been published by Nichols, et al. (1995).

In this phase of the project, four two-bay X-braced frames were pushed to collapse (Figure 4). The effects of joint ductility and system redundancy on the ultimate and post-ultimate response of the frames were studied. The frames were heavily instrumented and tested in plane. The hydraulic actuators were located at the top of the frames and were operated in a displacement-controlled manner. The frames were pinned at the bottom. The four frames had virtually the same geometry but differed in the joint can thickness, horizontal bracing, initial imperfections and residual stresses. Frame 2 was similar to frame 1 with the exception of a reduced joint can thickness. Frame 3 was virtually the same as frame 1 with the horizontal brace at the mid height removed. Finally frame 4 had the same configuration as frame 3 with the difference of locked-in prestresses and initial imperfections. Frame test 4 was left. out of the verification study.

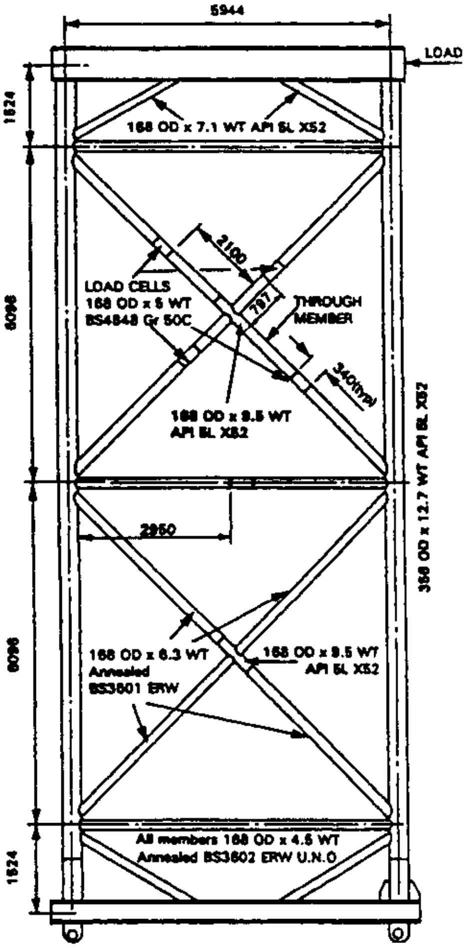

Figure 4: Test Program II - Test Frame Geometry (After Bolt et al.,1994)

The test results for frames 1 and 3 are shown in Figure 5 in terms of lateral load displacement. In the case of frame 1, the buckling of the compression brace at the top half of the upper bay was reported to govern the ultimate lateral capacity of the frame which was reached at a lateral load of 920 kN. Due to redundancy of the X-bracing configuration and existing horizontal brace at the mid-height, a substantial residual strength in the system could be observed (Figure 5). Portal action in the legs was also reported to have contributed to this residual capacity.

In the case of frame 3, a similar failure mode was observed. However, the peak lateral resistance was reached at a load level of 780 kN. The lower capacity as compared to the frame 1 was reported to be due to differences in the residual stresses and not a result of the missing horizontal brace at the mid-height. The lower residual capacity was, however, attributed to the reduced redundancy and lack of an effective load redistribution after first member failure. This resulted in a premature buckling of the compression brace in the lower bay and a consequent rapid fall of lateral resistance in post-ultimate regime (Figure 6).

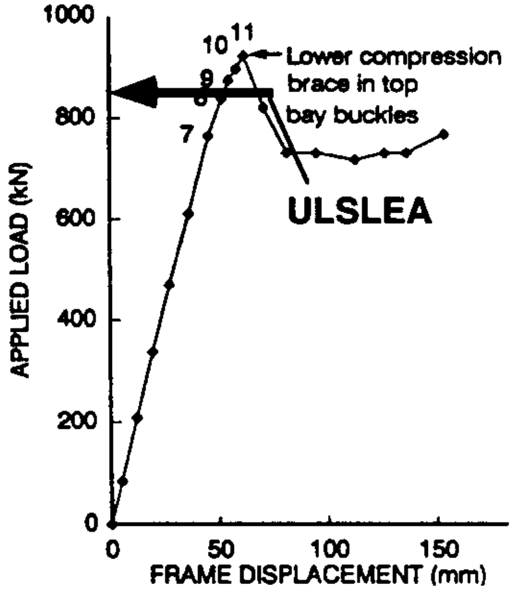

Figure 5: Test Program II - Tests 1 (After Bolt, et al., 1994)

ULSLEA was used to predict the ultimate lateral capacity of both frames 1 and 2. ULSLEA predicted almost simultaneous failure of the compression and tension diagonals at the upper bay at a lateral load of roughly 850 kN for both frames. This result is in excellent agreement with the test results. The minor difference is due to the fact that ULSLEA does not account for residual stresses. The fact that the absence of the horizontal bracing in frame 3 did not change the ultimate capacity of the system, confirms the assumption made in ULSLEA regarding horizontal framings. In ULSLEA, it is assumed that horizontal bracings exist and are rigid.

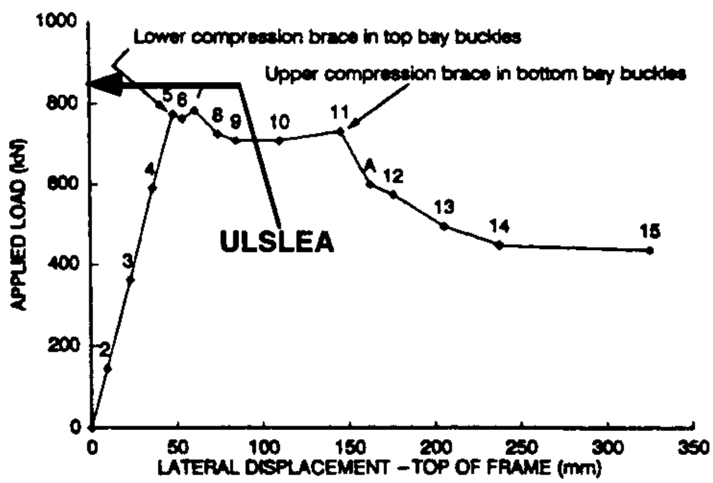

Figure 6: Test Program II - Test 3 - No Horizontal Bracing at Mid-Height (After Bolt, et al., 1994)

The results of the frame test 2 are plotted in Figure 7. The X-joint in the upper bay with the reduced wall thickness was the weak link in the frame and started yielding at a lateral load of 689 kN. The flattening of the joint essentially postponed the buckling of the compression diagonal and the tension diagonal developed its full yield strength. After the X-joint was completely compressed, a new load path was created. With further increase in the lateral load, the compression brace in the upper bay buckled and a rapid load shedding followed. The large global deflection at collapse had also resulted in portal action. The peak capacity of 1,080 kN was reached.

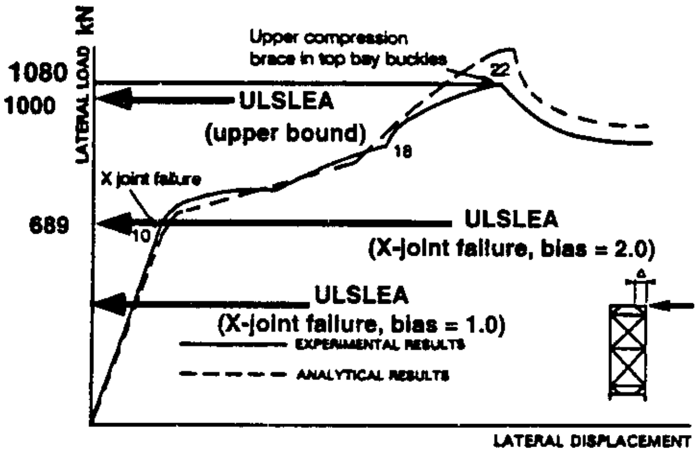

Figure 7: Test Program II - Test2 (After Bolt, et al., 1994)

ULSLEA underestimated the lateral load at first member failure by 50%. The first member to fail was the X-joint in the upper bay. This underprediction is due to the conservatism of the joint capacity equations as given by API RP 2A-LRFD and used in ULSLEA. Based on use of a joint capacity bias factor of 2 resulted in an ULSLEA predicted lateral capacity of 689 kN; a very close prediction of the lower-bound capacity. An upper-bound capacity of 1,000 kN was predicted by ULSLEA. This peak lateral load was predicted to be associated with simultaneous failure of the tension and compression diagonals. The test indicated a peak lateral load capacity of 1,080 kN. In this case, the minor difference between ULSLEA and test results was traced back to the additional frame resistance due to portal action in the test.

FRAME TEST PROGRAM III

This frame test program was the second phase of the BOMEL's Frames Project (Bolt, 1995). Two objectives of this phase of the program were to investigate the effect of boundary conditions on joint ultimate capacity performance and to examine the collapse behavior of K-braced frames. In this phase four single bay K-braced frames were laterally pushed to collapse (Figure 8). Gap and overlap K-joints were used. The frames were laterally pushed under displacement-control beyond the ultimate load and into post-ultimate regime in order to capture their residual strength.

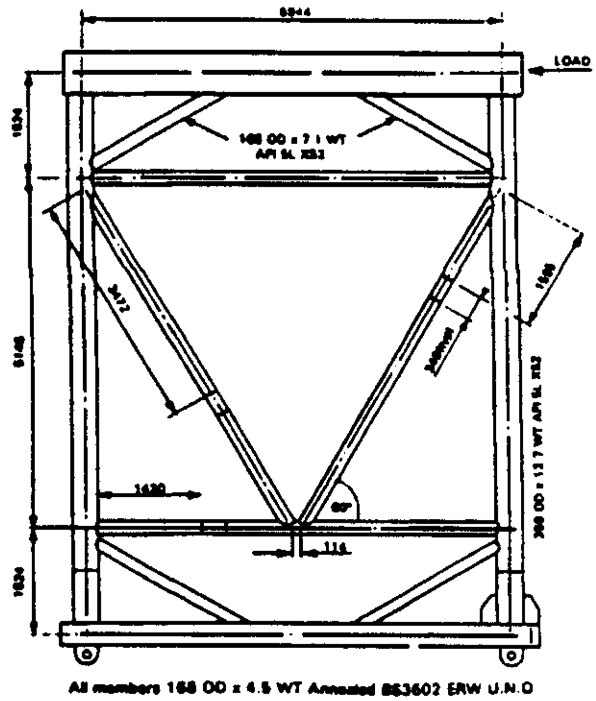

Figure 8: Test Program III - Test Frame Geometry (After Bolt, 1995)

Figure 9 shows the load displacement behavior of one of the frames. The ultimate capacity was governed by the failure of the K-joint. With increasing lateral load, a crack was initiated at the chord side of the tension brace, which rapidly propagated and led to load shedding and a sudden reduction in frame lateral resistance.

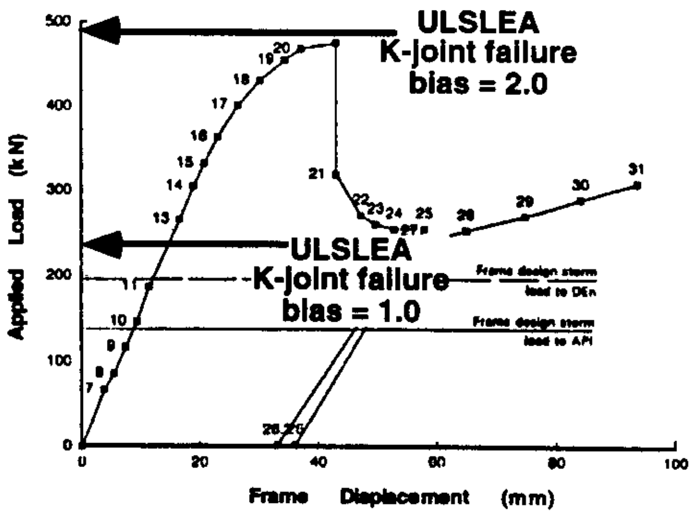

Figure 9: Test Program III (After Bolt, 1995)

Compared to test results on isolated joints, it was found that the joint capacity within frames was higher. ULSLEA also predicted K-joint failure, however at a lateral load 50% lower than reported in the test; 230 kN (Figure 9). Again, the difference was found to be due to the conservatism in joint capacity formulations in API-RP 2A-LRFD (API, 1993b). Once the bias in the API joint formulation (= 2.0) was input to ULSLEA, the lateral load capacity was evaluated to be 460 kN. This was very close to the measured lateral capacity of 470 kN.

SUMMARY

Table 1 contains a summary of the verification studies based on frame test results. First member failures and ultimate lateral loading capacities of six test frames were predicted using the simplified method. These results were compared with the actual performance of the test frames. Defining a bias as the ratio of test over ULSLEA results, the mean and coefficient of variation of the bias were estimated to be 1.05 and 0.1 respectively for the cases where brace failures governed the capacity. In cases where tubular joint failures governed the frame capacity, the mean and coefficient of variation of the bias were estimated to be 2.03 and 0.01 respectively. The latter set of results can be explained by the conservatism of the API joint capacity equations (API, 1993b) which are integrated into ULSLEA. Once a bias of 2.0 in the API joint capacities are recognized, the ULSLEA results are very close to the measured frame lateral load capacities.

Table 1 : Capacity Predictions - Comparison of ULSLEA and Test Results

Frame Test	Summary Description	Failure Category	Test Result Failure Mode	Test Result Base Shear	ULSLEA Failure Mode	ULSLEA Base Shear	Ratio of TEST/ULSLEA Base Shears
IA	single bay, K-braced, overlap K-joint	1st member failure	comp. brace	160 kips	comp. brace	160 kips	1.00
		ultimate capacity	comp. brace	160 kips	comp. brace	160 kips	1.00
IB	single bay, K-braced, overlap K-joint, grouted compression diagonal	1st member failure	tension brace	240 kN	all braces	240 kN	1.00
		ultimate capacity	all braces	300 kN	all braces	240 kN	1.25
IIA	two bay, X-braced, strong X-joint cans	1st member failure	comp. brace top bay	920 kN	comp. brace top bay	850 kN	1.08
		ultimate capacity	comp. brace top bay	920 kN	comp. brace top bay	850 kN	1.08
IIB	two bay, X-braced, weak X-joints	1st member failure	X-joint top bay	689 kN	X-joint top bay	345 kN	2.00
		ultimate capacity	all braces top bay	1080 kN	all braces top bay	1000 kN	1.08
IIC	two bay, X-braced, strong X-joint cans, no horizontal bracing	1st member failure	comp. brace top bay	780 kN	comp. brace top bay	850 kN	0.92
		ultimate capacity	comp. brace top bay	780 kN	comp. brace top bay	850 kN	0.92
III	single bay, K-braced, gap K-joint	1st member failure	K-joint	470 kN	K-joint	230 kN	2.04
		ultimate capacity	K-joint	470 kN	K-joint	230 kN	2.04

CONCLUSIONS

ULSLEA has been verified in two generations of studies with results from nonlinear inelastic analyses of approximately 30 platforms. ULSLEA has been able to develop evaluations of the lateral capacities of these platforms that are very close to those determined from the nonlinear analyses.

Many of these platforms were subjected to intense hurricane loadings, bringing several of the platforms close to failure or actually failed the platforms. As long as the substantial conservative biases incorporated into current API guidelines for pile and joint capacities are recognized, then ULSLEA is able to develop results that are in conformance with the observed performane of these platforms.

The results summarized in this paper indicate that ULSLEA is able to develop lateral load capacity results that are very close to the lateral load capacities from frame tests. Again, it is important to recognize the conservative biases in the API joint capacities, reasonable effective length factors for the compressive braces, and the expected steel yield strengths.

ULSLEA has been verified with results from analyses, from the performance of platforms in the field, and from frame tests. The authors believe that ULSLEA will prove to be a very useful tool for platform reanalyses and requalifications, preliminary design, parametric studies, and for checking results from complex nonlinear analyses of offshore platforms.

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